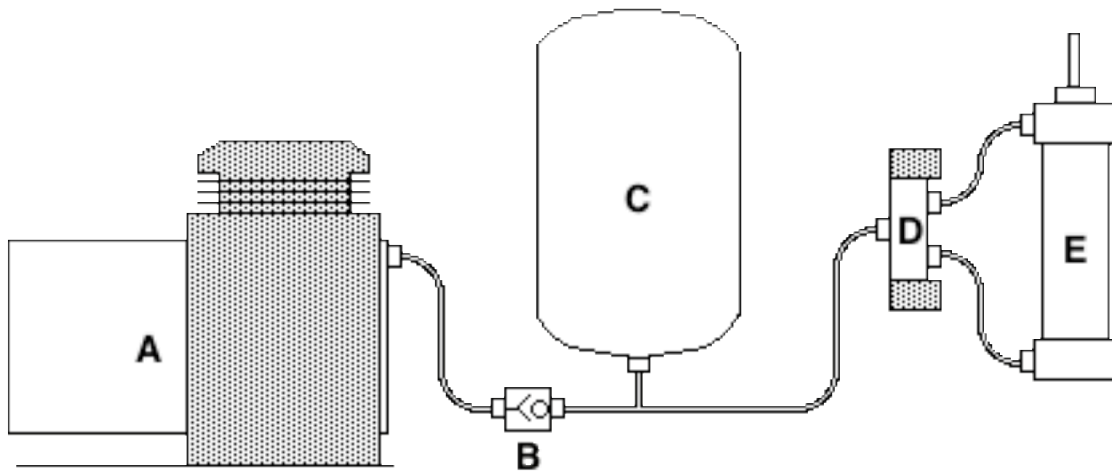


Elements of a basic pneumatic system:



A – Compressor: a pump which compresses air, raising it to a higher pressure, and delivers it to the pneumatic system (sometimes, can also be used to generate a vacuum).

B – Check valve: one-way valve that allows pressurized air to enter the pneumatic system, but prevents backflow (and loss of pressure) into the compressor when it is stopped.

C – Accumulator: stores compressed air, preventing surges in pressure and relieving the duty cycle of the compressor.

D – Directional valve: controls the flow of pressurized air from the source to the selected port. Some valves permit free exhaust from the port not selected. These valves can be actuated either manually or electrically (the valves typically provided in the FIRST kits use dual solenoids to change the direction of the valve, based on input signals from the control system).

E – Actuator: converts energy stored in the compressed air into mechanical motion. A linear piston is shown. Alternate tools include rotary actuators, air tools, expanding bladders, etc.

Pneumatic System Design Notes

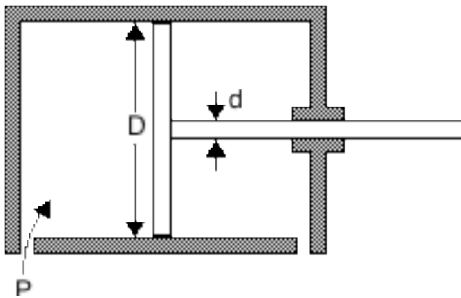
Constants:

- 1 mm = 0.0394 inches
- 1 square mm = 0.0016 square inches
- 1 litre = 0.0353 cubic feet
- 1 bar = 14.50 psi

As we design a pneumatic system of the type used in the FIRST competitions, we want to know three things:

- how much force can an actuator apply?
- is that force sufficient to move the desired load?
- how fast can the load be moved?

To determine how much force an actuator can apply, we need to calculate the **Theoretical Force**. For a pneumatic piston actuator, that is determined by multiplying the surface area of the moving piston by the pressure applied. In other words, for a round piston:



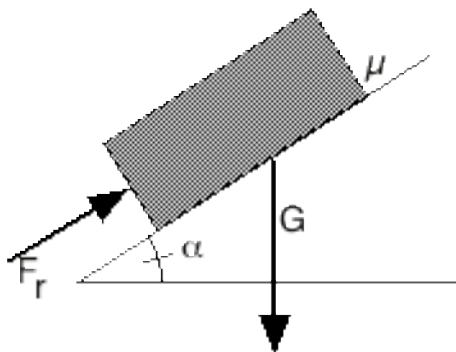
$$F_t = \pi * D^2/4 * P$$

Where D is the diameter of the piston and P is the working pressure of the injected air. Note that on the reverse stroke of the piston, the available surface area of the piston is decreased by the area of the piston rod. In that case:

$$F_t = \pi * (D^2 - d^2)/4 * P$$

Note this does not account for inefficiencies in the actuator due to friction between the piston and the cylinder wall, the piston rod and the packing gland, stiction forces, etc. For our purposes, these factors contribute to an approximate 5% loss in efficiency (i.e. the practical force available from the piston is about 95% of the calculated force).

Next, we need to know how much force is required to move the object we want to move. To determine the **Required Force**, we need to know the mass of the object to be moved, the direction of motion relative to gravity, and the effects of any friction between the object to be moved and whatever is supporting it. To calculate the required force, use:



$$F_r = G * (\sin \alpha + \mu * \cos \alpha)$$

where G is the mass of the object to be moved, α is the angle of inclination that the mass will move (between -90 and 90 degrees), and μ is the coefficient of friction between the moving object and any supporting structure or surface (μ may vary between 0.1 and 0.4 for sliding metal-on-

metal parts, or about 0.005 for iron rolling on iron as in a ball bearing, etc.).

The **Load Ratio** is the relationship between the force required to move the load and the available force from the actuator. The load ratio is determined by:

$$\text{Load ratio} = (\text{Required Force} / \text{Theoretical Force}) * 100 \%$$

In theory, the load ratio must be 100% or lower to be able to perform the task. In practical applications, the load ratio should be 85% or lower. Also note that if the actuator is able to deliver more force than the minimum needed to move the load, then the excess force delivered by the actuator is used to accelerate the load. In other words:

$$\text{Acceleration Force (F}_a\text{)} = \text{Theoretical Force (F}_t\text{)} - \text{Required Force (F}_r\text{)}$$

From the first lesson on forces and accelerations, we know that

$$\text{Acceleration (A)} = \text{Force (F}_a\text{)} / \text{Mass (G)}$$

$$\text{Distance (d)} = 1/2 * \text{Acceleration (A)} * \text{Time (t)}^2$$

Knowing the acceleration of the object and the distance to be traveled (the stroke of the piston), we can calculate the time required for the object to move from rest to the end of the piston stroke (remember that the value of G is determined by the weight of the object divided by acceleration due to gravity; 32 ft/sec² for English units, or 9.8 m/sec² for metric). Note that this theoretical acceleration is based on the assumption that there is an instantaneous supply of compressed air, and there is no back pressure on the back side of the piston. Each of these factors limits the practical acceleration of the load.

The effects of these limiting factors can be reduced by applying a number of strategies when designing the pneumatic system. A very complex set of calculations can be used to evaluate the different design parameters, or we can use a set of “Rules of Thumb” which result in approaches that are close enough for our purposes. These are captured below.

“Rules of thumb” for pneumatic design:

- Larger tubing, valves and fittings are preferable to smaller (large diameter tubing adds less resistance to the air flow than smaller tubing)
- For a given tubing size, the shorter the run, the better (long tubing runs add resistance to the air flow from the source to the fittings and actuators)
- The straighter the tubing run, the better (bends and curves induce turbulence, which slows the flow of air into the fittings and actuators)
- The fewer valves (and other fittings), the better (fittings add resistance to the air flow)
- The higher the air pressure, the better (for a given equivalent flow section, this gives a higher flow rate)
- For bi-directional piston actuators, place the control valve as close to the actuator as possible (this reduces the back pressure on the exhaust side of the piston)

Example and problems:

A 100 pound object needs to be lifted vertically one foot. You have a 2-inch diameter piston actuator with a 12-inch stroke connected to a 50 psi source of pressurized air. The mass is restricted by a set of guide rails, which limit it to vertical motion, and which use roller bearings with a friction coefficient of 0.002. Can the object be lifted? How long will it take?

The theoretical force of the piston is $(\pi * 2^2/4 * 50) = 157$ lb. With a 5% efficiency loss, the available force is 149 lb ($157 \text{ lb} * 95\%$).

Since the mass is being lifted vertically, the inclination angle θ is 90° . So, the required force is $100 \text{ lb} * (\sin 90^\circ + 0.002 * \cos 90^\circ) = 100$ lb. This is well below the theoretical force, so the object can be lifted. The load ratio is $(100 \text{ lb} / 149 \text{ lb}) * 100 = 67.1\%$

The acceleration force is $(149 \text{ lb} - 100 \text{ lb}) = 49$ lb. Therefore, the acceleration is $(49 / (100/32)) = 15.75 \text{ ft} / \text{sec}^2$, or $189 \text{ inches} / \text{sec}^2$. With this acceleration, the object can be raised 12 inches in about 0.35 seconds ($12 = 1/2 * 189 * t^2$, solve for t).

Now you try...

Our robot weighs 120 pounds. The kit of robot parts includes a pump that can produce compressed air at 22 psi. We want to mount a linear piston underneath the robot that will lift it straight up by expanding between the underside of the robot and the floor. What is the minimum recommended piston size that is required to lift the robot?

Extra notes (for those interested):

Flow rate of air through the system can be determined by using the formula:

$$Q = 22.2 * S * \sqrt{(p_2 + 1.013) * (p_1 - p_2)}$$

Where p_1 is the pressure on the high pressure end of the system (measured in bar), p_2 is the pressure on the low pressure end of the system (measured in bar), and S is the equivalent flow section (measured in mm^2). For our purposes, the “equivalent flow section” is the cross-section measurement of the smallest tube, valve or orifice in the system, reduced by an efficiency factor of about 25%. Q is measured in litres per minute of flow.

This formula is valid for subsonic gas flow. The calculations change significantly when sonic or supersonic flow rates are involved.